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# CHANDRA X-RAY OBSERVATORY DETECTION OF EXTENDED X-RAY EMISSION FROM THE PLANETARY NEBULA BD +30°3639

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## ABSTRACT

We report the detection of well-resolved, extended X-ray emission from the young planetary nebula BD +30°3639 using the Advanced CCD Imaging Spectrometer (ACIS) aboard the *Chandra* X-ray Observatory. The X-ray emission from BD +30°3639 appears to lie within, but is concentrated to one side of, the interior of the shell of ionized gas seen in high-resolution optical and IR images. The relatively low X-ray temperature ( $T_x \sim 3 \times 10^6$  K) and asymmetric morphology of the X-ray emission suggest that conduction fronts are present and/or mixing of shock-heated and photoionized gas has occurred, and furthermore hints at the presence of magnetic fields. The ACIS spectrum suggests that the X-ray-emitting region is enriched in the products of nuclear burning. Our detection of extended X-ray emission from BD +30°3639 demonstrates the power and utility of *Chandra* imaging as applied to the study of planetary nebulae.

*Subject headings:* planetary nebulae: individual (BD +30°3639) — stars: mass loss — stars: winds, outflows — X-rays: ISM

## 1. INTRODUCTION

Planetary nebulae (PNs) represent the last stages of evolution for stars of initial mass  $1\text{--}8 M_\odot$ . The central star that generates a PN has terminated its asymptotic giant branch (AGB) evolution, but its ejected stellar envelope has yet to disperse entirely, such that the star's newly exposed hot core (the eventual white dwarf remnant) ionizes and illuminates the envelope via UV radiation. The photoionized gas in a typical PN is far too cool to emit X-rays, and the central stars are, at best, sources of very soft X-rays. However, theorists have long predicted that high-temperature X-ray emission should arise from a so-called “hot bubble” formed inside the optically emitting ionized gas (e.g., Kwok, Purton, & Fitzgerald 1978; Mellema & Frank 1995). The hot bubble is formed when the new, fast ( $\sim 1000 \text{ km s}^{-1}$ ) wind emanating from the white dwarf rams into the ejected red giant envelope that is coasting outward at  $\sim 10 \text{ km s}^{-1}$ , in principle shock-heating the material to above  $10^7$  K.

*Einstein* and *ROSAT* detected X-rays from more than a dozen planetaries (de Korte et al. 1985; Tarafdar & Apparao 1988; Apparao & Tarafdar 1989; Zhang, Leahy, & Kwok 1993; Leahy, Zhang, & Kwok 1994; Rauch, Koeppen, & Werner 1994; Chu & Ho 1995; Hoare et al. 1995; Leahy et al. 1996; Chu, Chang, & Conway 1997; Chu, Gruendl, & Conway 1998; Chu, Guerrero, & Gruendl 2000), but in most cases the X-ray spectra are quite soft ( $T_x \leq 2 \times 10^5$  K) and therefore clearly emanate from hot central stars rather than hot bubbles (Guerrero, Chu, & Gruendl 2000 and references therein). However, a handful of planetaries do display rather hard spectra, in data obtained with the *ROSAT* Position-Sensitive Proportional Counter (PSPC). The brightest, hardest, and therefore most convincing example among the *ROSAT* PSPC detections was

the compact young planetary nebula BD +30°3639 (Kreysing et al. 1992), whose high X-ray temperature ( $T_x \sim 3 \times 10^6$  K) was subsequently confirmed by *ASCA* (Arnaud, Borkowski, & Harrington 1996). Furthermore, Leahy, Kwok, & Yin (2000) found the X-ray-emitting region of BD +30°3639 to be possibly extended in *ROSAT* High Resolution Imager (HRI) data.

BD +30°3639 is a fascinating object in many other respects as well. Its youth is apparent from the compact morphology and low ionization state of its H II region, the low temperature of its central star ( $T_* \sim 30,000$  K), and its large ratio of neutral to ionized gas mass (Sahai & Trauger 1998; Leahy et al. 2000; and references therein). Taken together these observations suggest that the onset of ionization in this nebula is a recent event. Furthermore,  $\sim 10^{-3} M_\odot$  of its neutral gas is concentrated in a pair of diametrically opposed “molecular bullets” that have been expelled at  $\sim 50 \text{ km s}^{-1}$  (Bachiller et al. 2000). The presence of such highly confined molecular outflows is strongly suggestive of the presence of a binary companion to the central star (see reviews in Kastner, Soker, & Rappaport 2000), and detection of these “bullets” called into question whether the interacting-winds model was applicable to BD +30°3639 (Bachiller et al. 2000).

With the launch of the *Chandra X-Ray Observatory*, it is possible for the first time to obtain subarcsecond images of X-ray sources and simultaneously to perform moderate-resolution X-ray spectroscopy, with the Advanced CCD Imaging Spectrometer (ACIS). In this Letter we report the unambiguous detection of extended X-ray emission from BD +30°3639. In a second paper (J. H. Kastner, S. Vrtilek, & N. Soker 2000, in preparation) we will present more detailed analysis of the BD +30°3639 data.

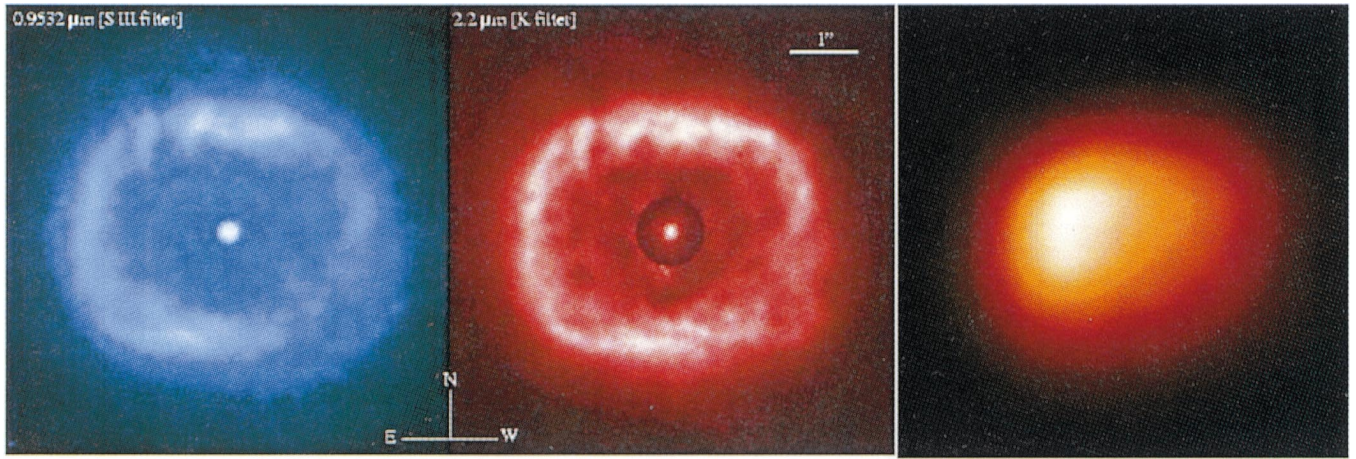


FIG. 1.—Optical (*left*), infrared (*middle*), and X-ray (*Chandra* ACIS; *right*) images of the planetary nebula BD +30°3639. The optical image was obtained by *HST* WFPC2 in [S III] at 9532 Å (Arnaud et al. 1996). The infrared image was obtained by Gemini equipped with adaptive optics camera (<http://www.ifa.hawaii.edu/ao/gemini/gemfl.html>) at 2.2 μm (*K* band). Images are presented at the same spatial scale.

## 2. OBSERVATIONS AND DATA REDUCTION

*Chandra* observed BD +30°3639, with ACIS as the focal plane instrument, on 2000 March 21. The duration of the observation was 18.8 ks. The Science Instrument Module was translated and the telescope was pointed such that the telescope boresight was positioned near the center of the spectroscopy CCD array (ACIS-S), and the image of BD +30°3639 appeared on the central back-illuminated CCD (device S3). The ACIS-S3 pixel size is  $0''.49$ . The *Chandra* X-Ray Center (CXC) carried out standard pipeline processing on the raw ACIS event data, producing an aspect-corrected, bias-subtracted, graded, energy-calibrated event list, limited to grade 02346 events (*ASCA* system). From this list, we constructed a broadband (0.3–10.0 keV) image and a pulse height spectrum. The image of BD +30°3639 was smoothed by replacing raw pixel counts with the running mean in a  $3 \times 3$  pixel box. The spectrum was extracted using

CXC software, which was used to construct a histogram of pulse heights for events contained within a circle of radius 10 pixels (a radius we judged to include all the X-ray flux from BD +30°3639). The broadband ACIS-S3 count rate within this aperture was  $0.244 \text{ counts s}^{-1}$ . The background count rate in a nearby, off-source region of equivalent area was negligible in comparison ( $\sim 0.002 \text{ counts s}^{-1}$ ).

## 3. DISCUSSION

The *Chandra* image of BD +30°3639 shows an extended region of X-ray emission that appears to lie within, and is concentrated to one side of, the interior of the elliptical shell of ionized gas seen in high-resolution optical and IR images (Figs. 1 and 2). The approximate extent of the X-ray-emitting region is  $5'' \times 4''$ , or  $\sim 5000 \times 4000 \text{ AU}$  (for an assumed distance of  $\sim 1 \text{ kpc}$ ; J. H. Kastner, S. Vrtillek, & N. Soker 2000, in preparation). However, the X-ray emission is quite asymmetric in comparison to the optical and infrared morphologies of BD +30°3639, with a compact “hot spot” apparent toward the northeast rim of the optical/IR nebulosity and little or no emission toward the southwest rim. This result confirms the viability of the interacting-winds model, but shows that another ingredient is necessary. In particular, the asymmetry suggests that the hot bubble is inhomogeneous in density, temperature, and/or abundance. Alternatively, a spatially varying absorbing column may be responsible for the asymmetry; note the close correspondence between the outline of X-ray emission and the inner “hole” seen in the IR nebulosity.

The central star of BD +30°3639 blows a fast wind at a velocity of  $v_f = 700 \text{ km s}^{-1}$  (Leueningham, Hamann, & Jeffery 1996). The shocked fast wind is expected to have a temperature of  $\sim 10^7 \text{ K}$ , and be distributed isotropically around the central star. However, we find here a much lower temperature (see below), and the X-ray emission is localized and asymmetric, suggesting that the X-ray emission results from cooler, clumpy gas. Such cooler and denser gas can result from mixing of the hot gas with cooler, nebular gas (Chu & Ho 1995; Arnaud et al. 1996) and/or from the presence of a heat-conduction front (Soker 1994). The latter possibility suggests that magnetic fields play an important role in determining the asymmetric X-ray emission morphology of BD +30°3639, since the presence of localized magnetic fields would suppress heat conduc-

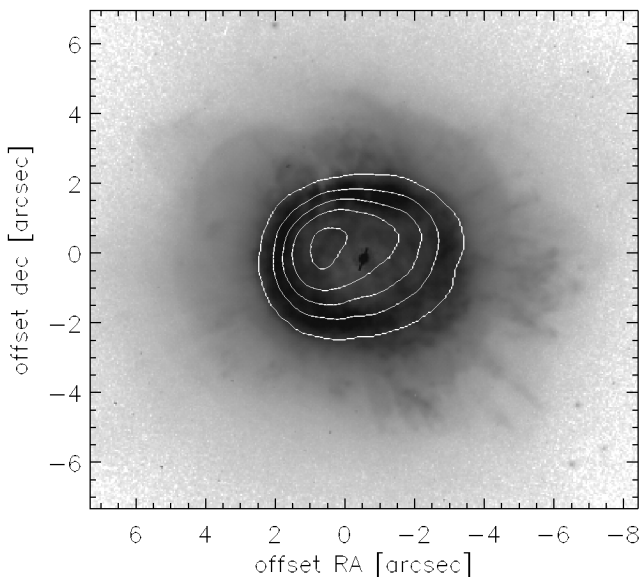


FIG. 2.—Contour map of *Chandra* X-ray image, overlaid on a gray-scale representation of an *HST* WFPC2 6563 Å  $H\alpha$  image (Sahai & Trauger 1998). The contours correspond to total counts of 10, 30, 50, 70, and 100 counts  $\text{pixel}^{-1}$  (integrated over the 18.8 ks observation).

tion, and therefore X-ray emission, in specific regions of the inner nebula (Soker 1994). More detailed analysis is postponed to our next paper (J. H. Kastner, S. Vrtilak, & N. Soker 2000, in preparation).

The *Chandra* ACIS spectrum of BD +30°3639 (Fig. 3) shows that nearly all the X-ray photons detected by ACIS have energies between 0.3 and 1.7 keV. The spectrum displays strong emission from a blend of He-like Ne lines centered at 915 eV, and an apparent blend of emission lines (and possibly continuum emission) between ~300 and ~700 eV. Fits of a variable-abundance MEKAL (Mewe-Kaastra-Liedahl collisional equilibrium) model indicate that the abundance of C is enhanced relative to solar, Ne is roughly solar, and N and O are depleted; these fits also suggest negligible abundances for all elements heavier than Ne. The apparent presence of significant continuum emission may indicate greatly enhanced He abundance, but this result is tentative, given the modest spectral resolution of ACIS. From the model fitting we deduce an emitting region temperature of  $T_x = 2.7 \times 10^6$  K ( $\pm 3\%$ ), intervening absorbing column of  $9.9 \times 10^{20}$  cm $^{-2}$  ( $\pm 4\%$ ), and absorbed flux of  $5.7 \times 10^{-13}$  ergs cm $^{-2}$  s $^{-1}$ . Assuming  $D = 1$  kpc, the model normalization and intrinsic (unabsorbed) flux indicate, respectively, an emission measure of  $5.0 \times 10^{54}$  cm $^{-3}$  ( $\pm 12\%$ ) and X-ray luminosity of  $L_x \sim 1.6 \times 10^{32}$  ergs s $^{-1}$ . This emission measure suggests an electron density of  $n_e \sim 200$  cm $^{-3}$ , given the approximate diameter of the emitting region; as noted above, however, the asymmetry of the *Chandra* image suggests that the emitting region is quite clumpy, and this result for  $n_e$  should only be considered an average value. Collectively, these results are consistent with those obtained by Kreysing et al. (1992) from *ROSAT* data and by Arnaud et al. (1996) from *ASCA* data, although analysis of the latter data set was complicated by contamination from a nearby supernova remnant.

The ACIS spectroscopy strongly suggests that the chemical abundances in the X-ray-emitting region are enriched in, and indeed may consist almost exclusively of, products of main-sequence and post-main-sequence nuclear burning. Furthermore, the large Ne abundance suggests that the nebula and white dwarf are the products of a relatively massive progenitor that obtained very high core fusion temperatures, and hence efficient production of Ne via the reaction  $^{16}\text{O} + \alpha \rightarrow ^{20}\text{Ne}$ . This interpretation relies on the results for CNO abundances, however, which can only be tentatively deduced, given the

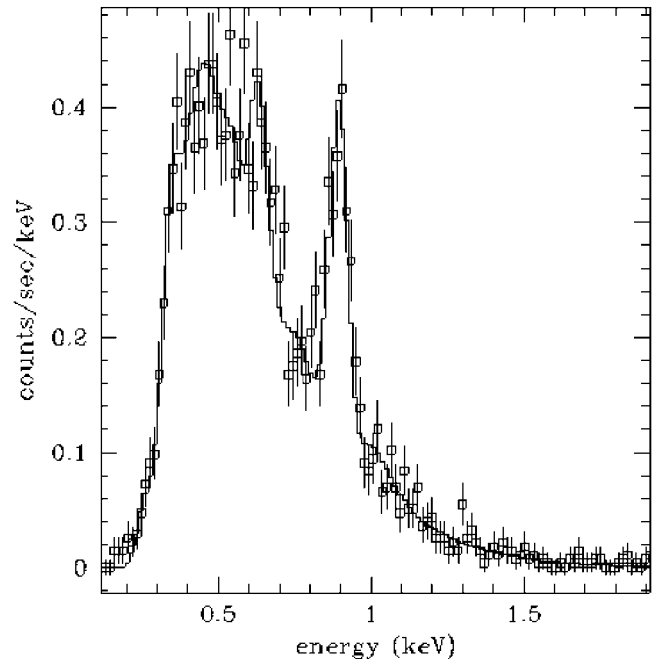


FIG. 3.—*Chandra* ACIS spectrum of BD +30°3639 (squares), with best-fit variable-abundance MEKAL model overlaid.

modest resolution of the CCD spectrum. The abundance anomalies implied by the X-ray spectrum may also hint at the central star's binary nature (Soker & Rappaport 2000).

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